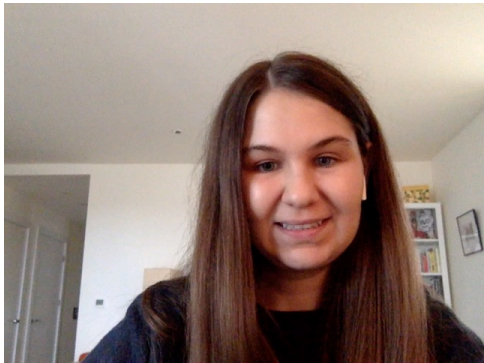
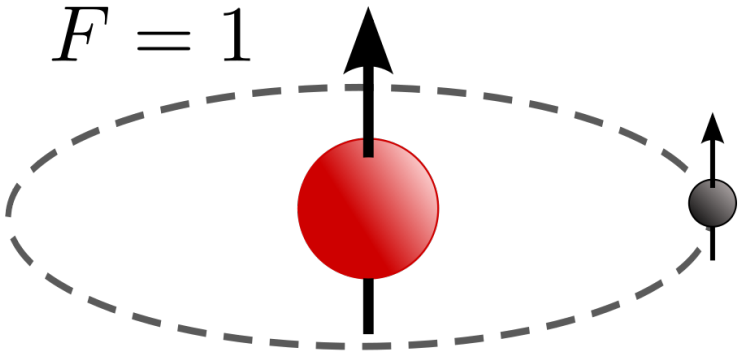
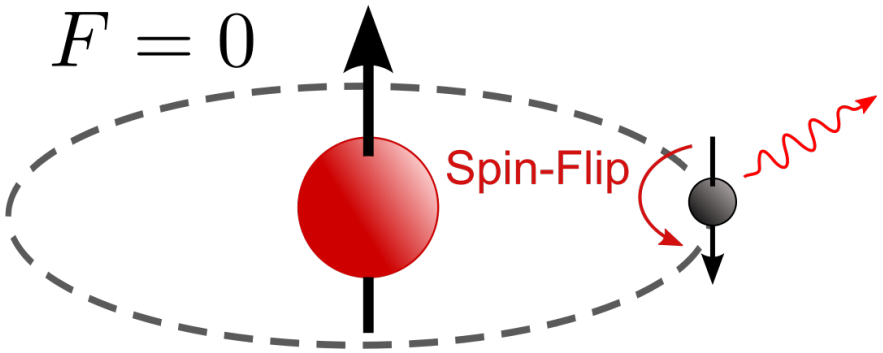
Anastasia Ponomareva
anastasia.ponomareva@physics.ox.ac.uk

The role of neutral hydrogen in the life of galaxies



The neutral hydrogen (HI) emission





$$\lambda = 21cm$$

$$f_0 = 1420.405751\ldots MHz$$

Predicted in 1944 by Hendrik van de Hulst
Observed in 1951 by Ewen and Purcell

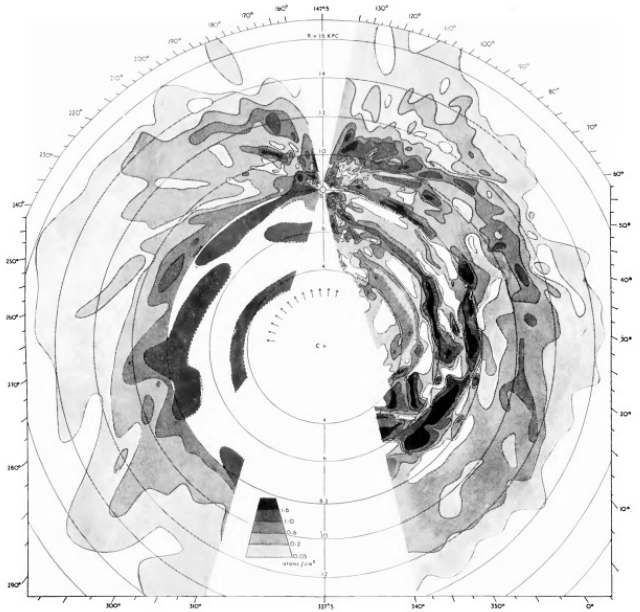
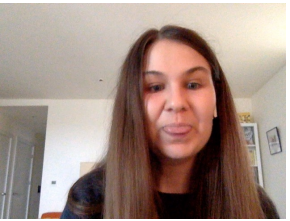


FIG. 4.—*Distribution of neutral hydrogen in the Galactic System. The maximum densities in the z-direction are projected on the galactic plane, and contours are drawn through the points.*

Oort, Kerr, F. J.; Westerhout, G., MNRAS, 1958



Why is it important? and What can we learn?

Galaxy structure and kinematics

ISM — warps, lopsidedness — rotation curves — angular momentum — non-circular motions

Accretion and depletion of gas onto galaxies

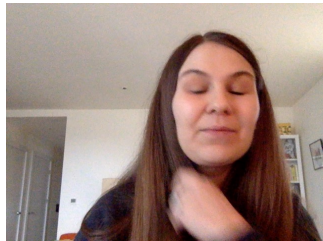
minor mergers — cold accretion — ram-pressure stripping — outflows and feedback

Formation of galaxies and large scale structure

HI mass function — major mergers — void population —cosmic web — distances

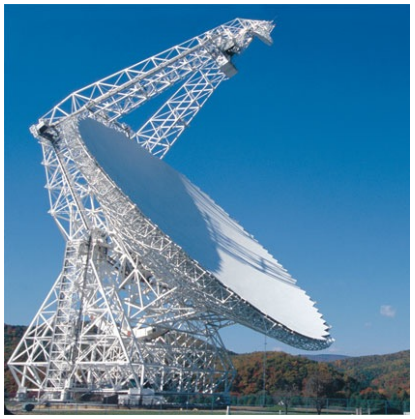
Cosmic evolution of gas in galaxies

$\Omega_{HI}(z)\ MHI(z)$ — gas fractions vs mass (stellar, baryonic, Dark Matter)

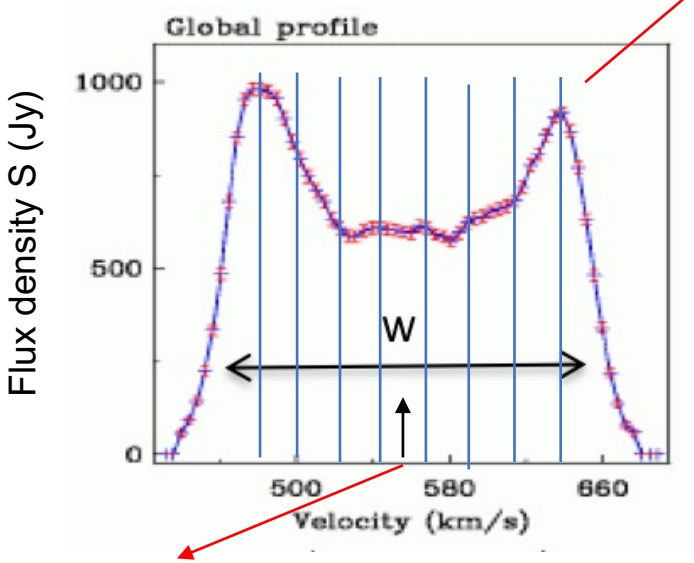


HI observations and observables

Green Bank Telescope (GBT)



Arecibo Telescope



dv - channel width / velocity resolution

Central (observed) frequency

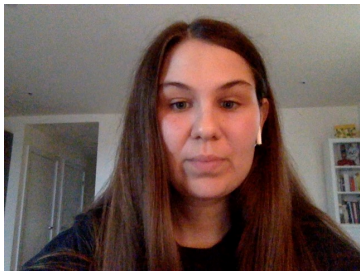
$$z = \frac{f_0 - fobs}{f_{obs}}$$

$$V_{sys} = \left(1 - \frac{f_{obs}}{f_0}\right) c$$

$$V_{rot} = W/\sin(i)$$

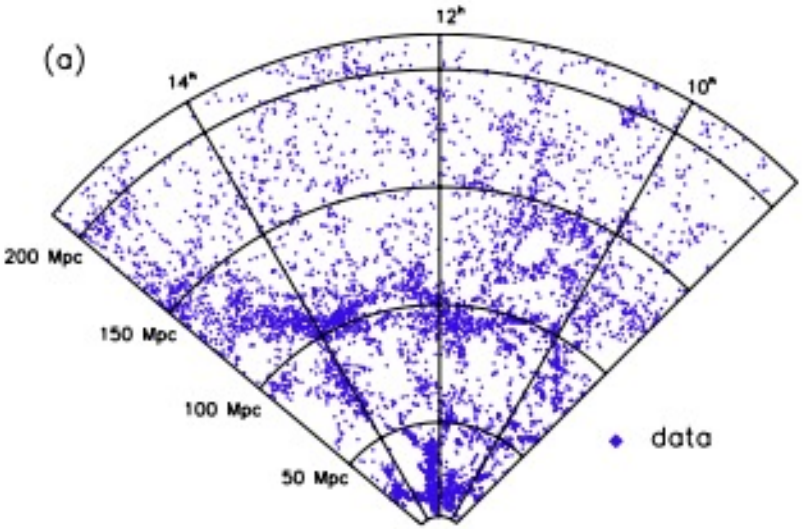
$$D = Vsys/H_0$$

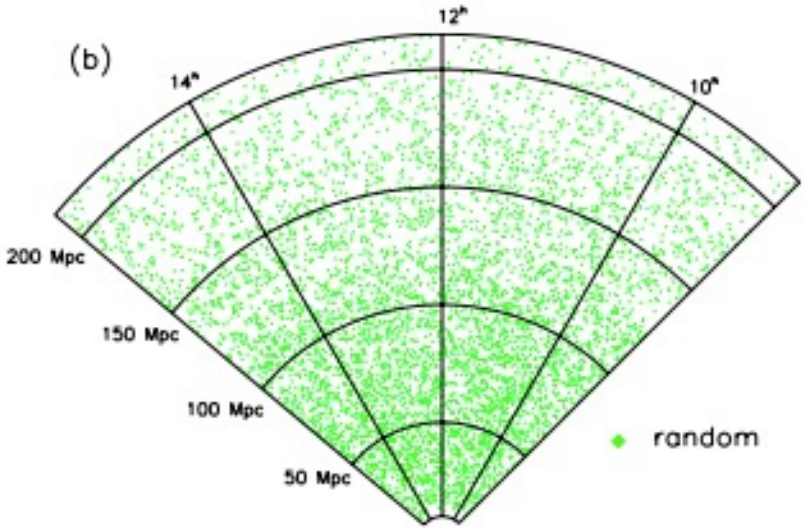
$$MHI\ [M\odot] = 2.36 \times 10^5\ D^2(Mpc) \int Sdv$$



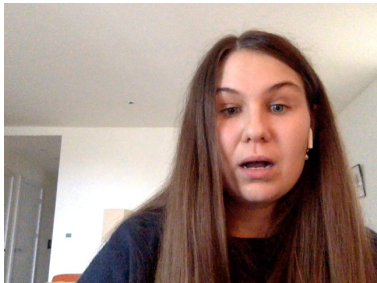
HI Large Scale Structure

ALFALAFA Survey



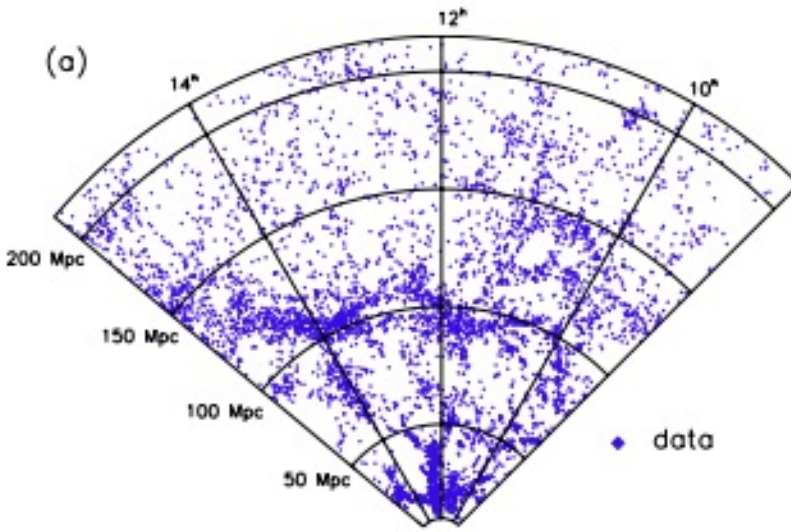


Papastergis+2013

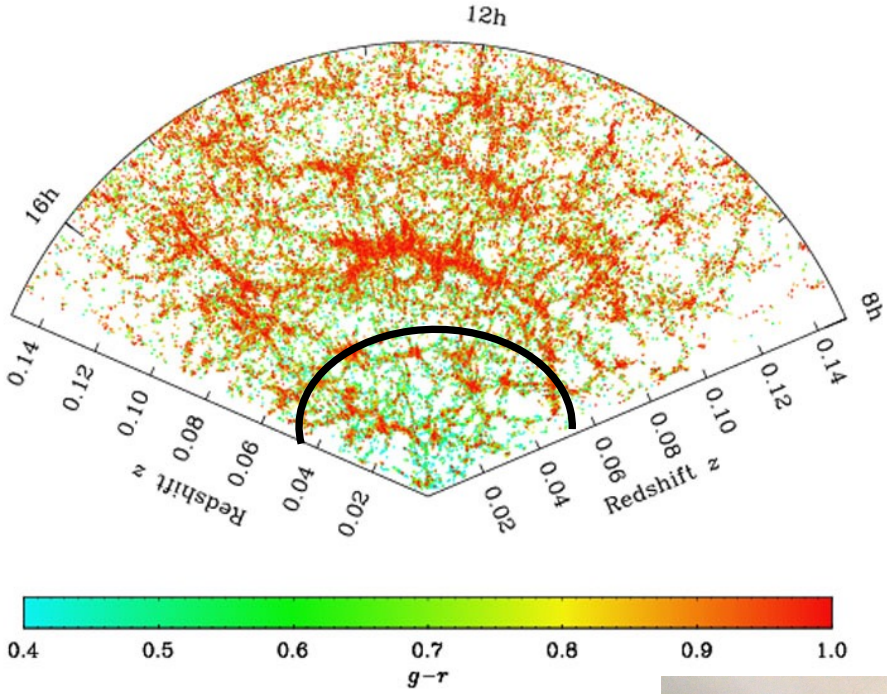


HI Large Scale Structure

ALFALAFA Survey



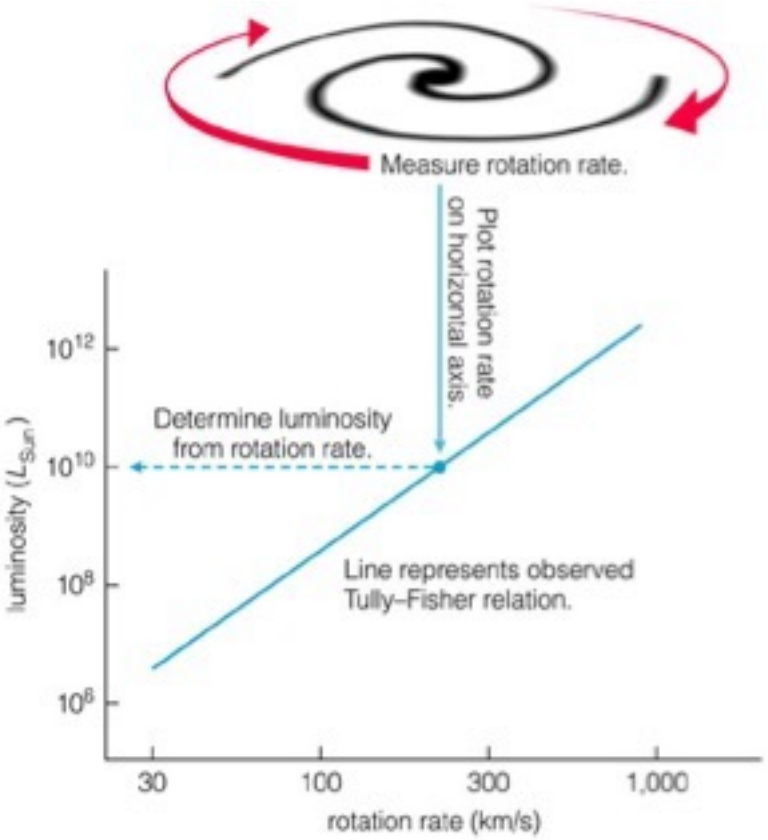
SDSS



Papastergis+2013

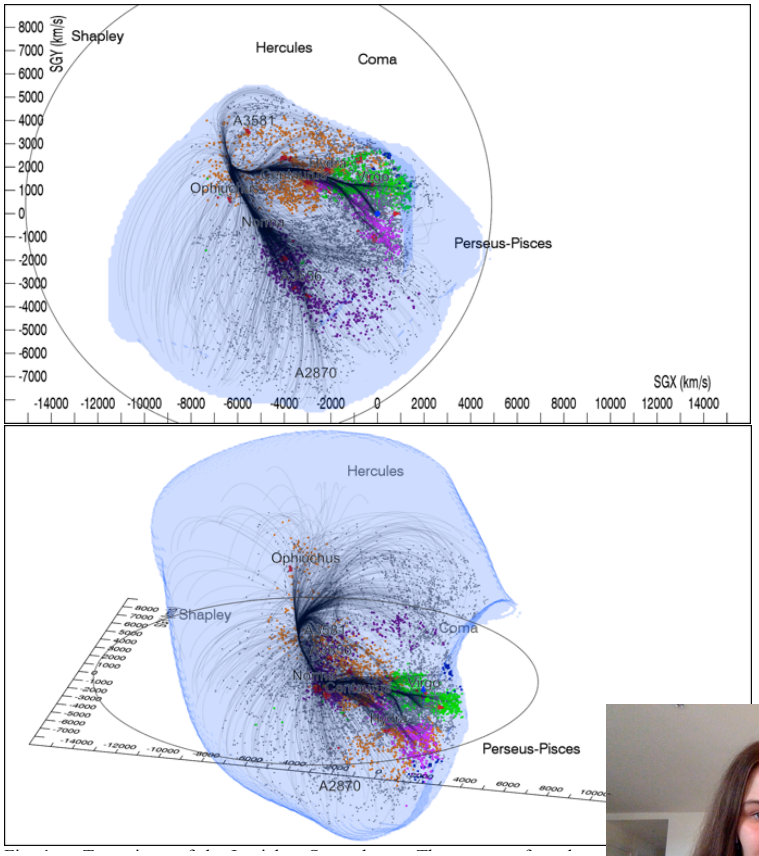
The Tully-Fisher relation

$$D = Vsys/H_0 \Longrightarrow V_{sys} = H_0 D + Vpec$$

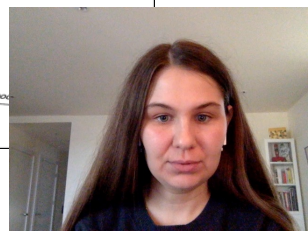


$$V_{rot} = W/\sin(i)$$

The Laniakea Supercluster



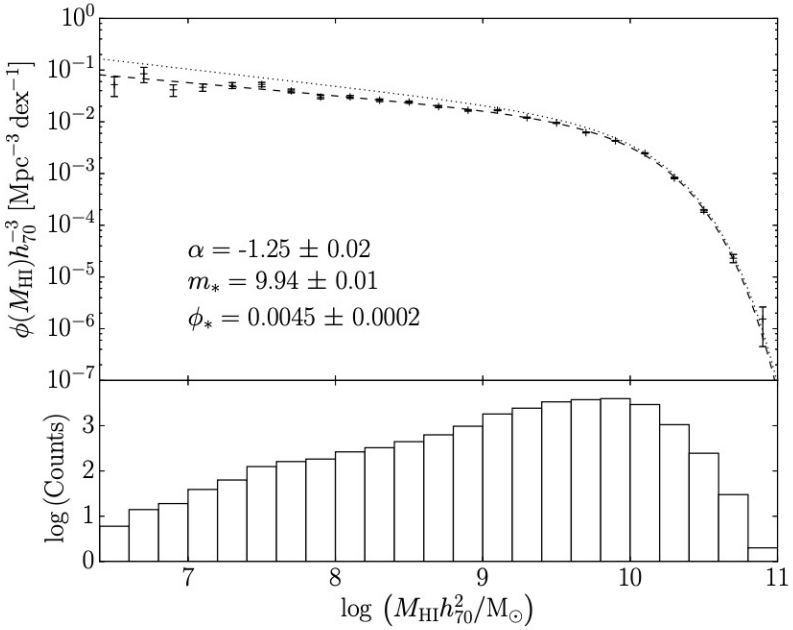
Tully+2014, Nature



ALFALFA Survey: HI global properties

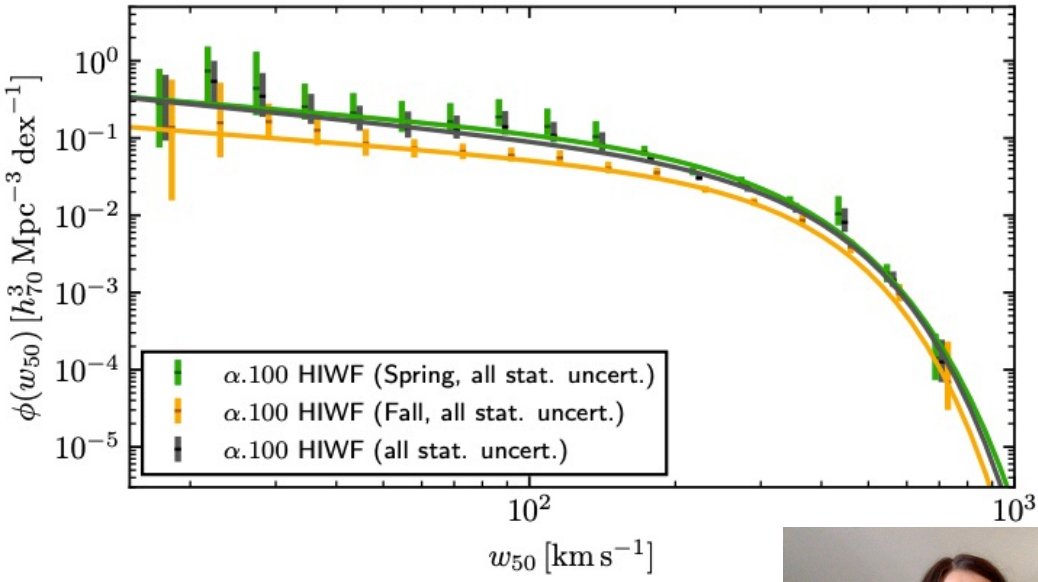
The HI mass function (HIMF) and HI velocity function represent the density distribution of HI masses and rotational velocities of galaxies in the Universe

HI mass function

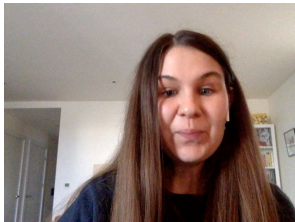


Jones+2013

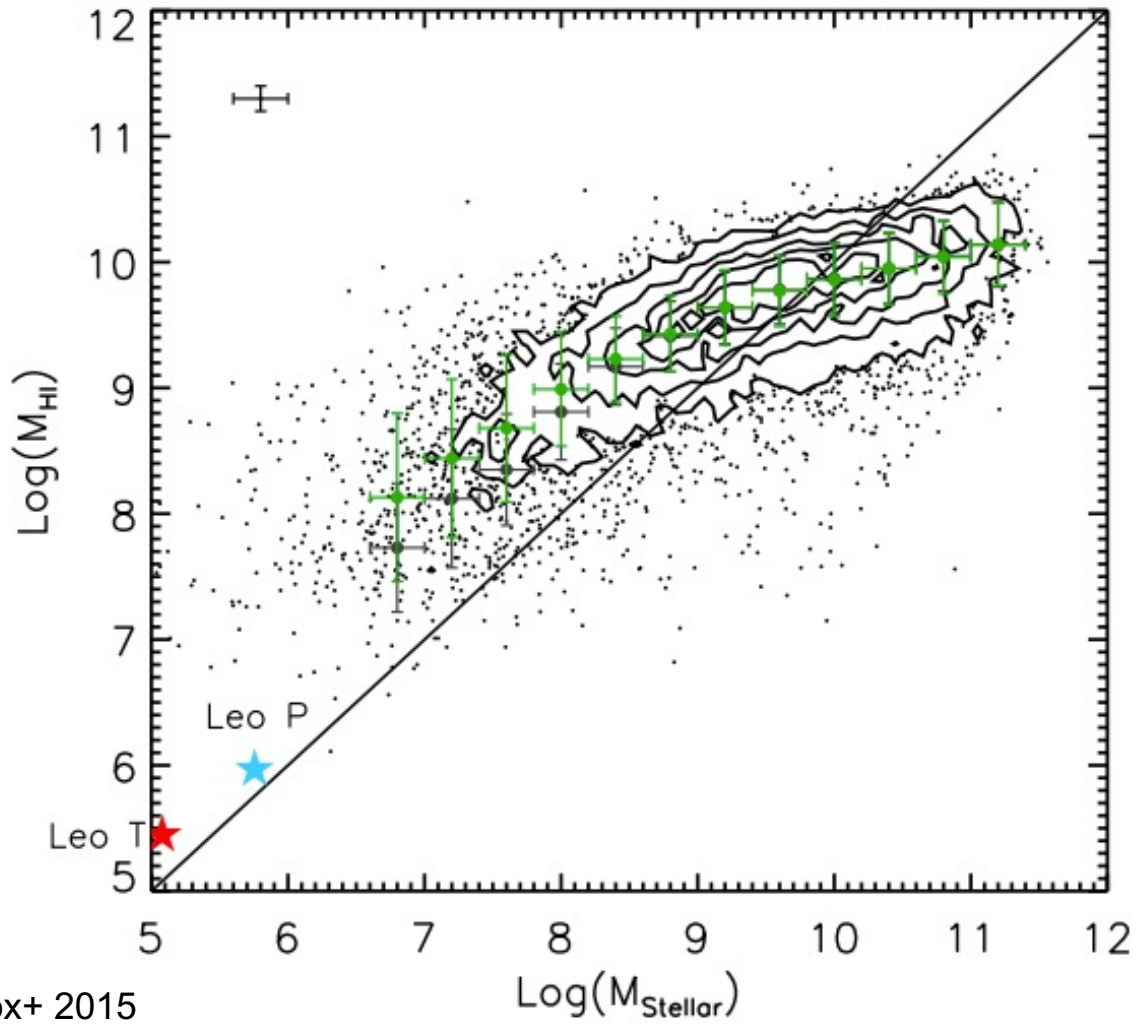
HI velocity function



Oman+2021

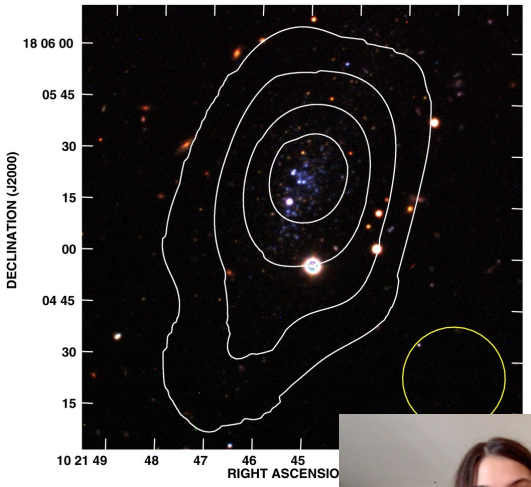


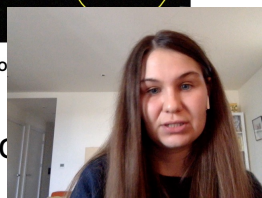
ALFALFA Survey: HI global properties



Maddox+ 2015

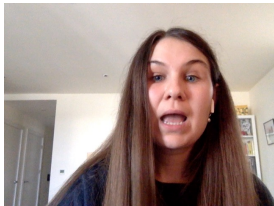
HI is a raw fuel for star formation, but stars do not form directly from HI





Take Home Messages I

- Observations of Neutral Hydrogen (HI) in galaxies open up a completely new window of galaxy formation and evolution mechanisms
- Global HI relations, such as HI mass vs Stellar mass, HIMF, HIVF and the TFR put important constraints on cosmological models of galaxy formation and evolution
- The neutral hydrogen serves as the raw material for the build-up of stellar mass

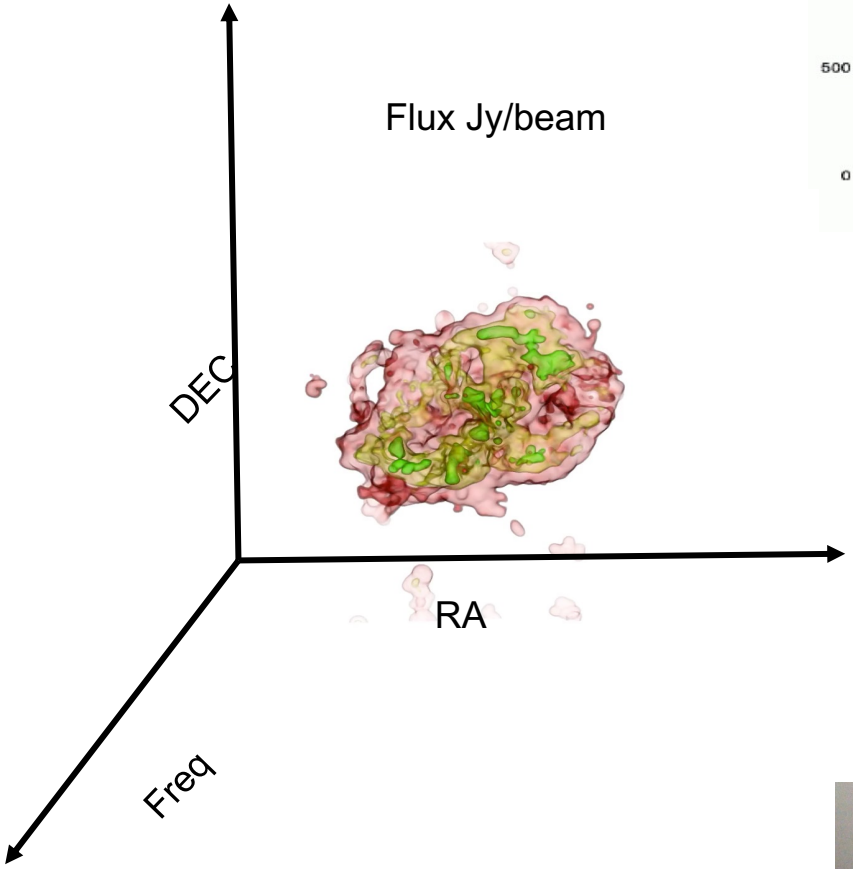


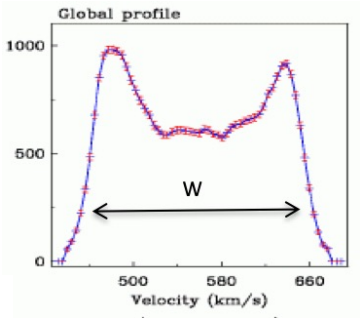
HI observations and observables

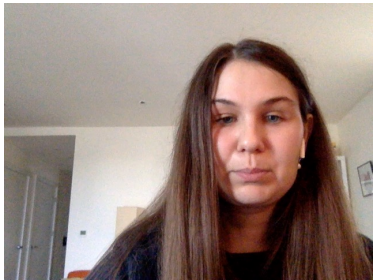
WSRT

VLA

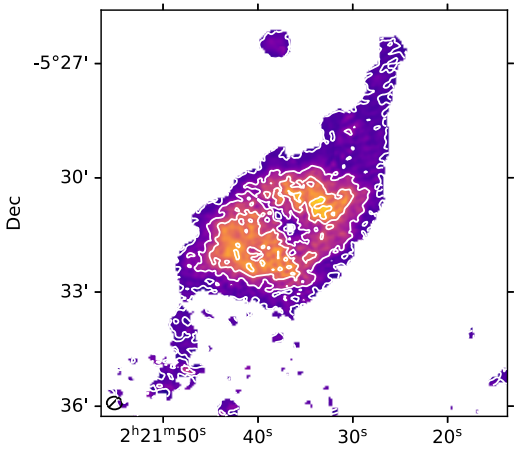
HI Radio Synthesis Imaging

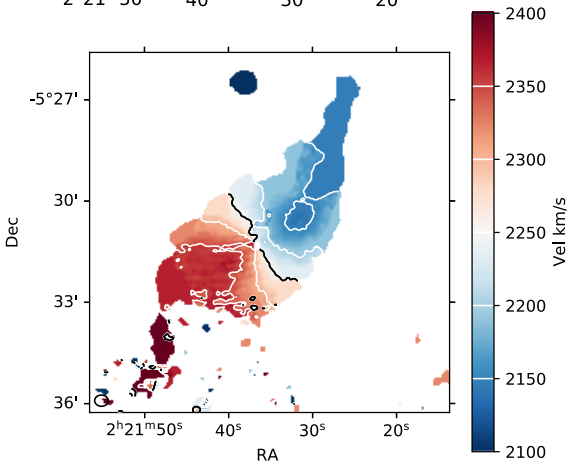


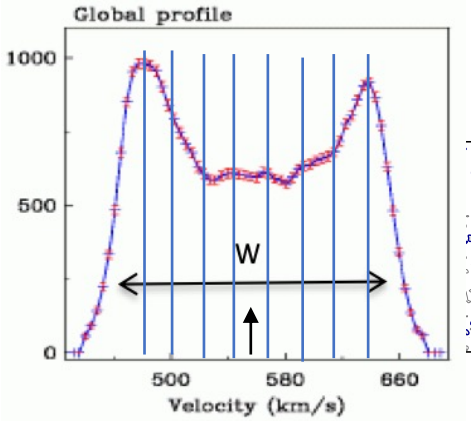


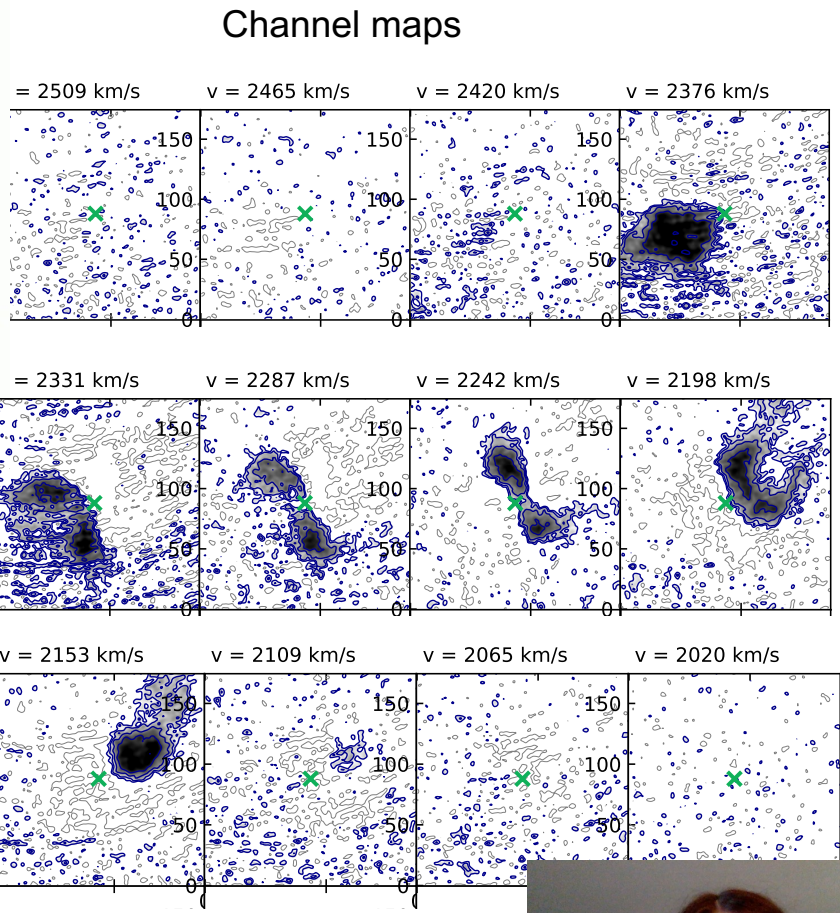


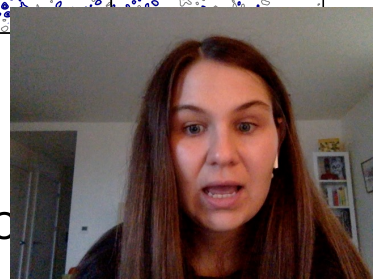
HI observations and observables





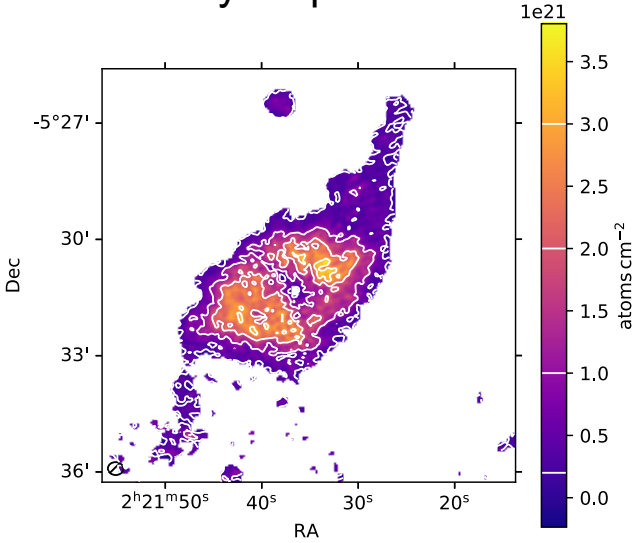




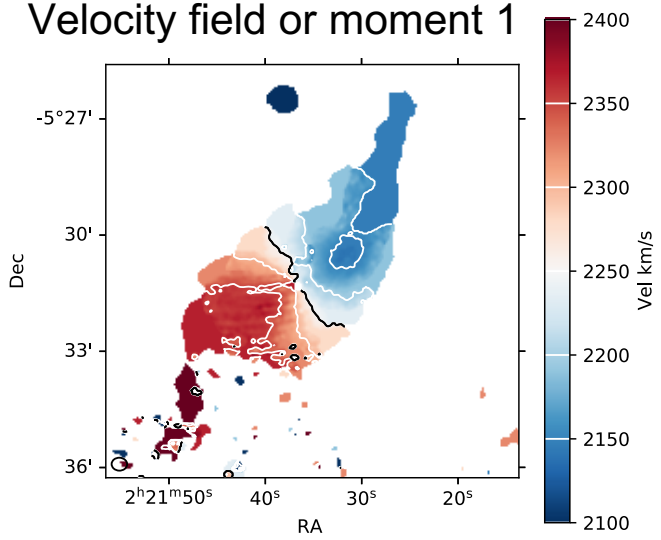


HI observations and observables

HI intensity map or moment 0



Velocity field or moment 1



HI column density

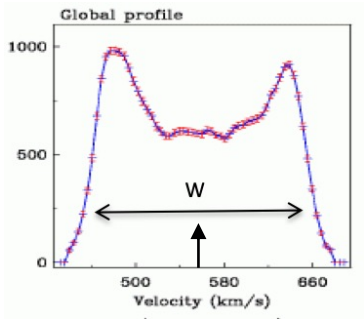
$$N_{HI} = 1.823 \times 10^{18} \int TbdV \; [atoms/cm^2]$$

HI Brightness Temperature

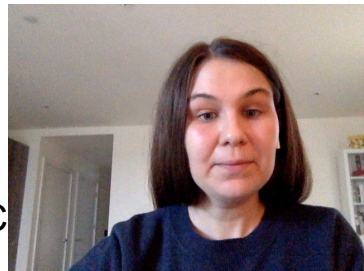
$$Tb = \frac{605.7}{\theta_x \theta_y} S \left(\frac{f_0}{f_{obs}}\right)^2$$

HI Surface mass density Σ_{HI}

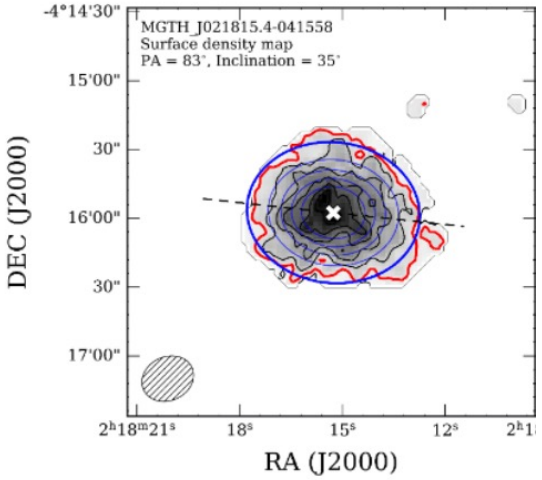
$$1 \; [M_\odot/pc^2] = 1.249 \times 10^{20} \; [atoms/cm^2]$$

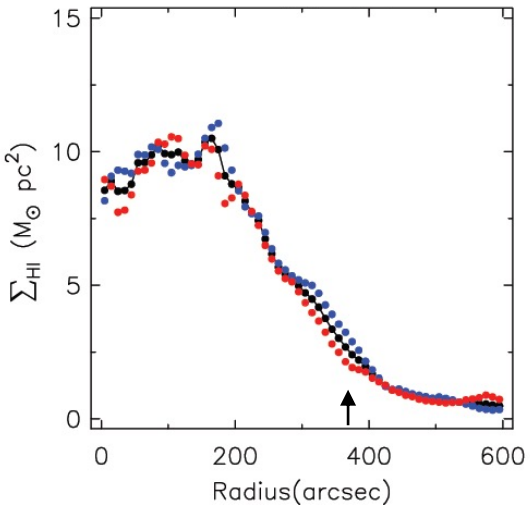


C



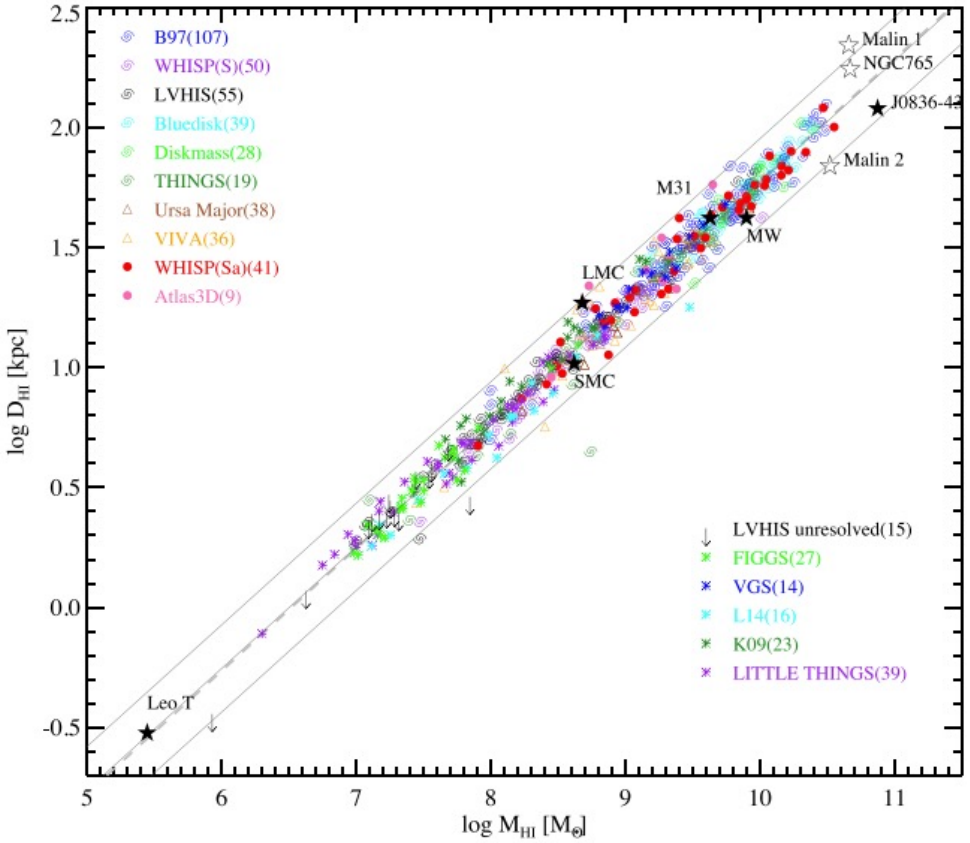
HI Mass - Size relation

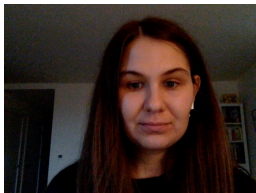




$$\log D_{HI} = (0.506 \pm 0.003) \log M_{HI} - (3.293 \pm 0.009)$$

$$\Sigma_{HI} = 4\frac{M_{HI}}{\pi {D_{HI}}^2} = 5.07\ M_\odot\ pc^{-2}$$

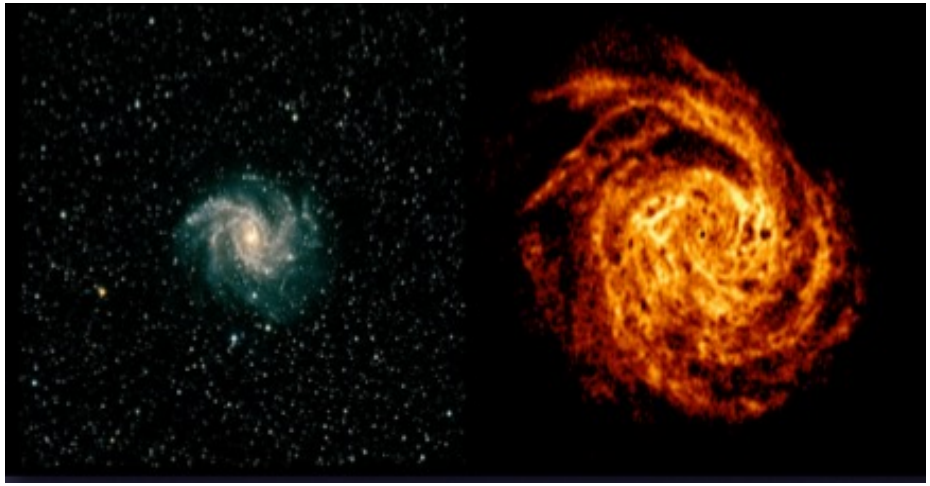




HI extends far beyond optical radius

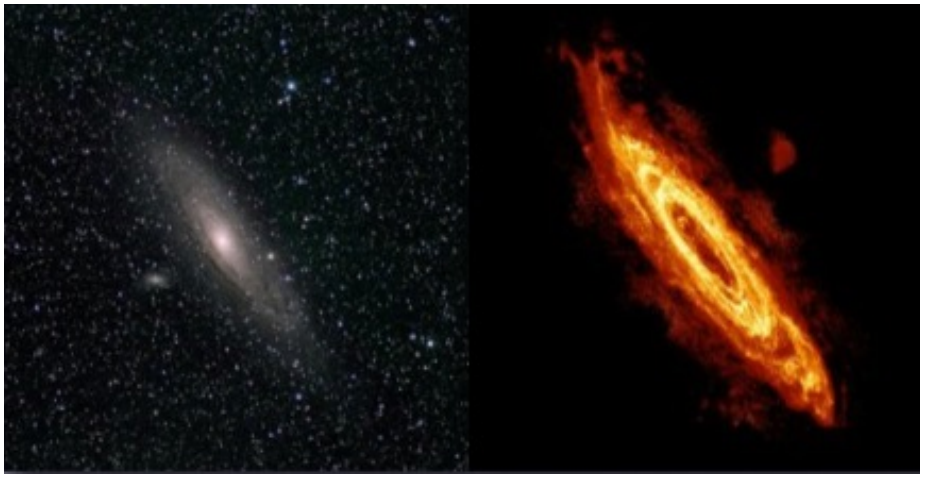
NGC 6946

Boomsma + 07

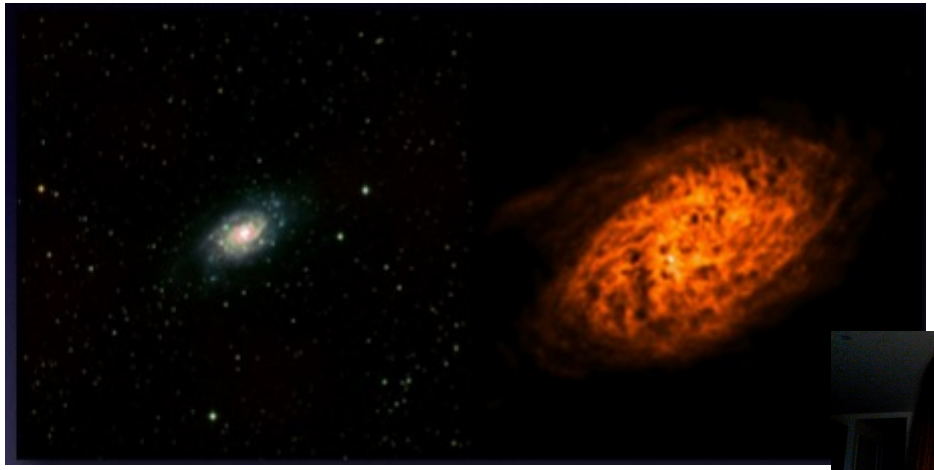


M 31

Braun + 09



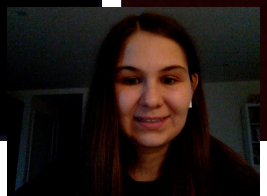
NGC 2403



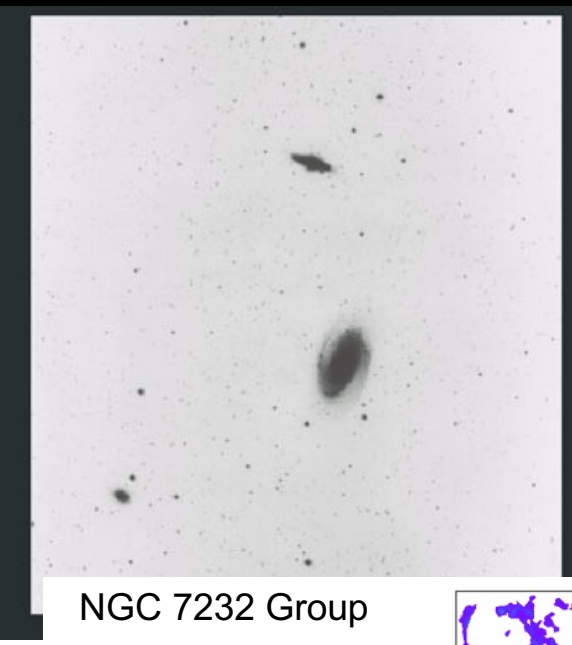
Fraternali + 01

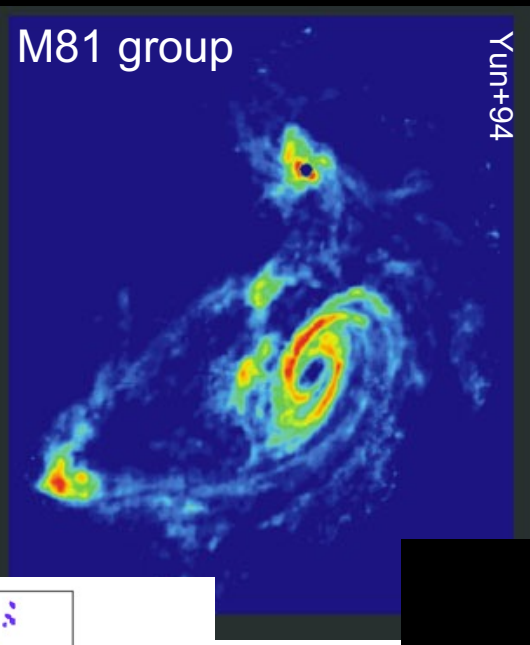
NGC 5055

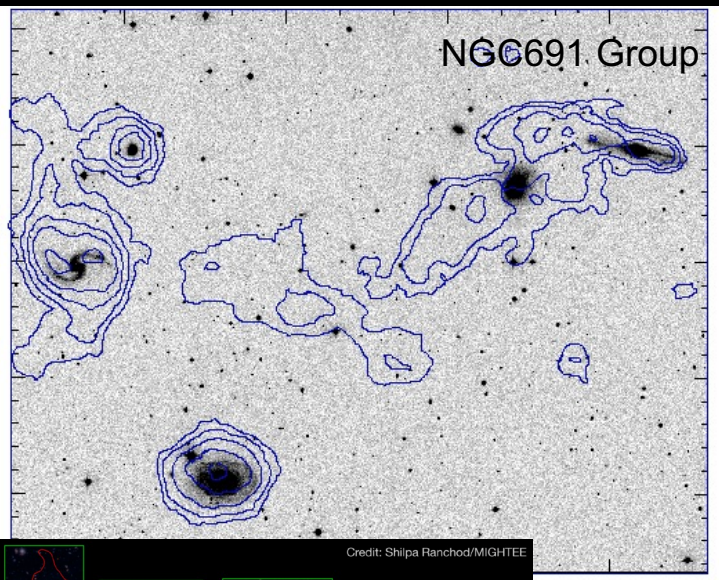
Battaglia + 05

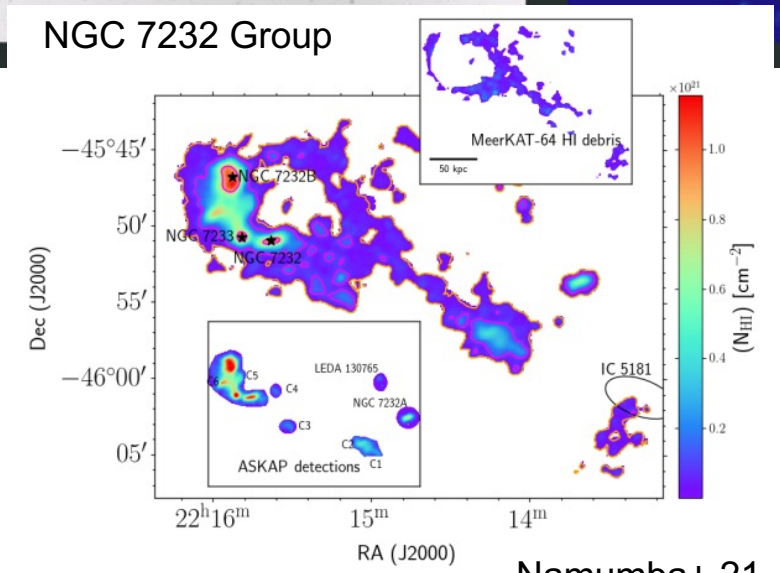


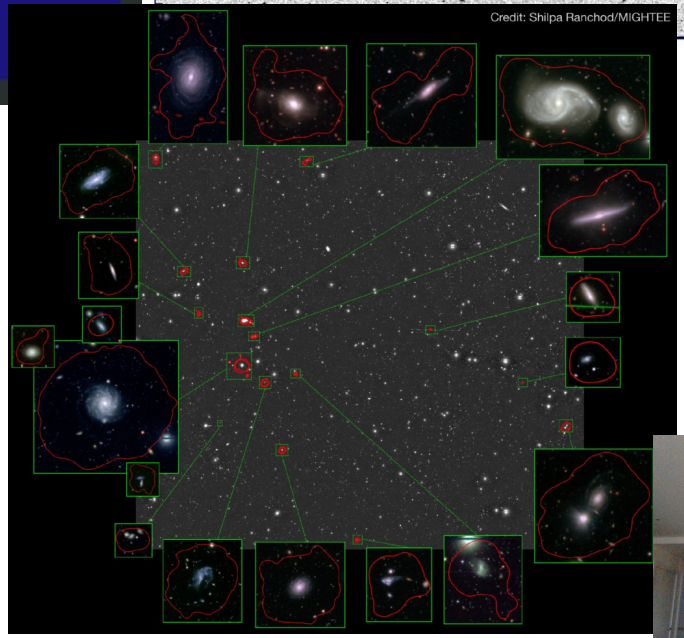
HI traces environment: Groups

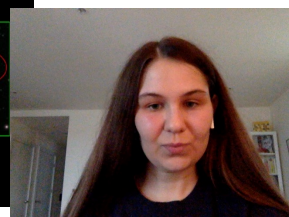




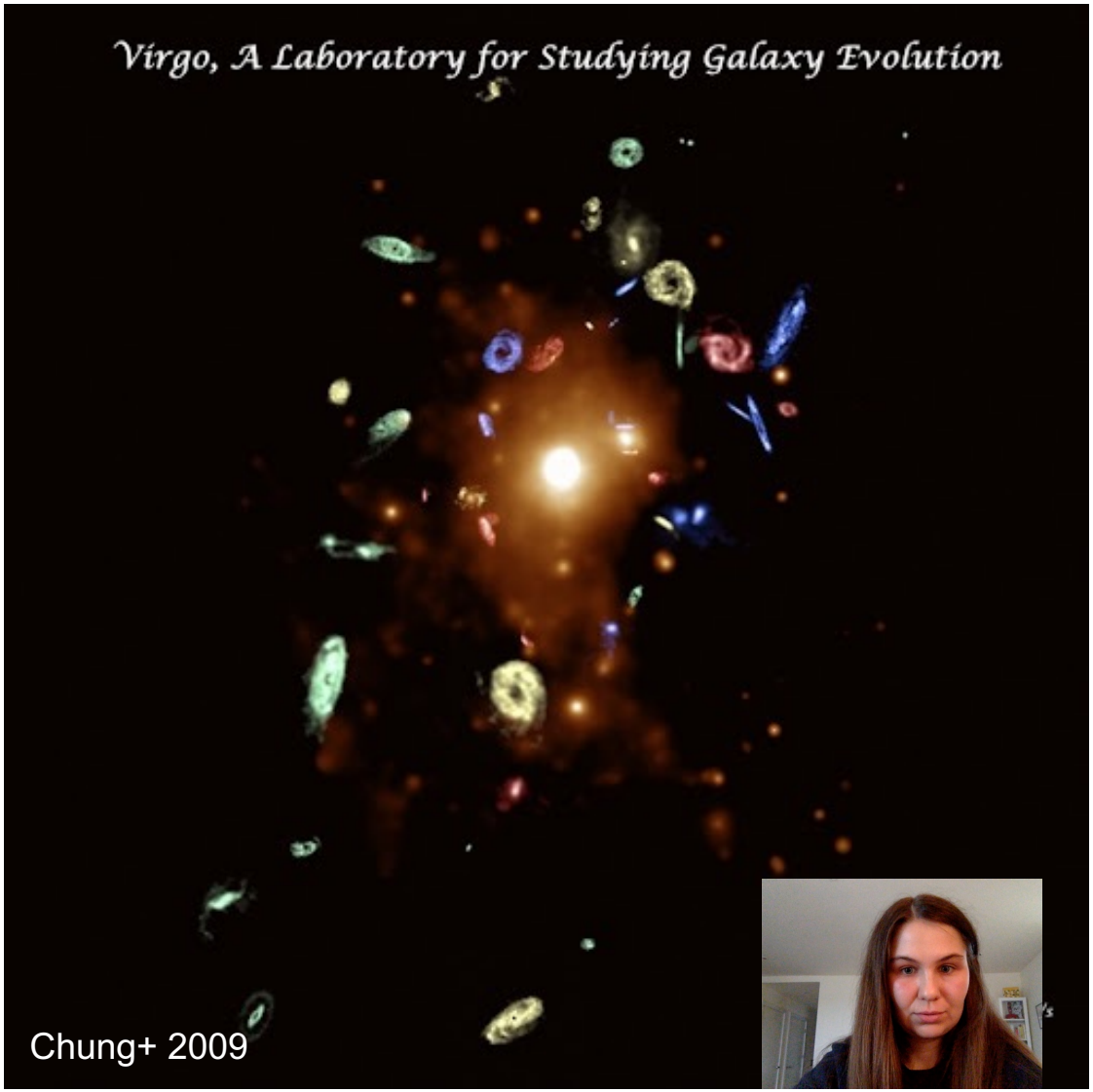




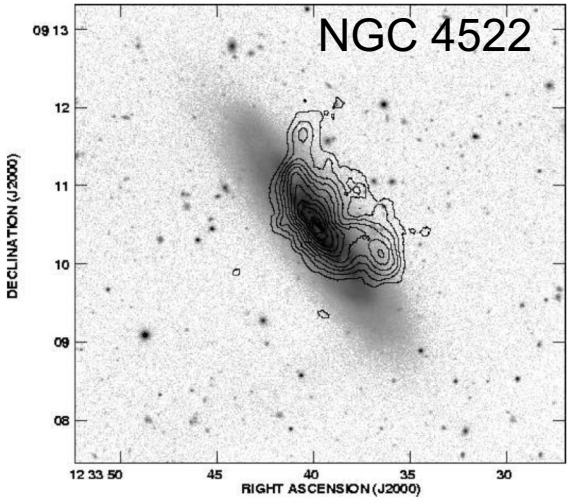




HI traces environment: Clusters



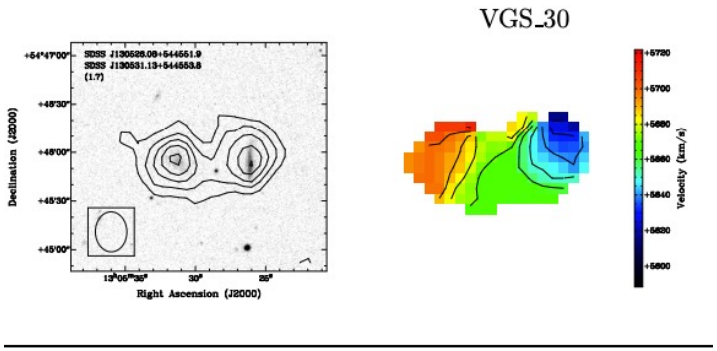
Chung+ 2009

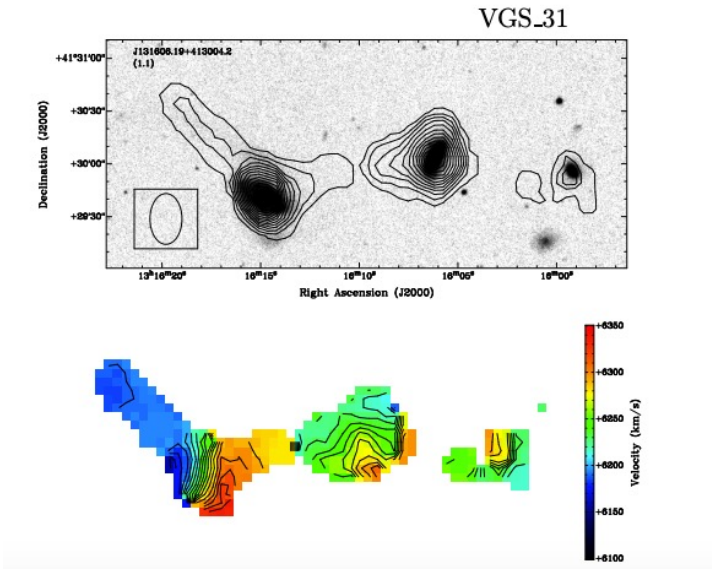


Kenney+04

HI traces environment: Voids

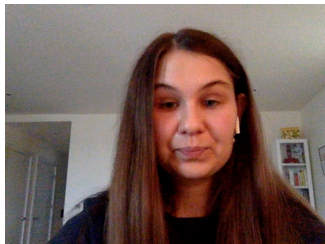
The Void Galaxy Survey





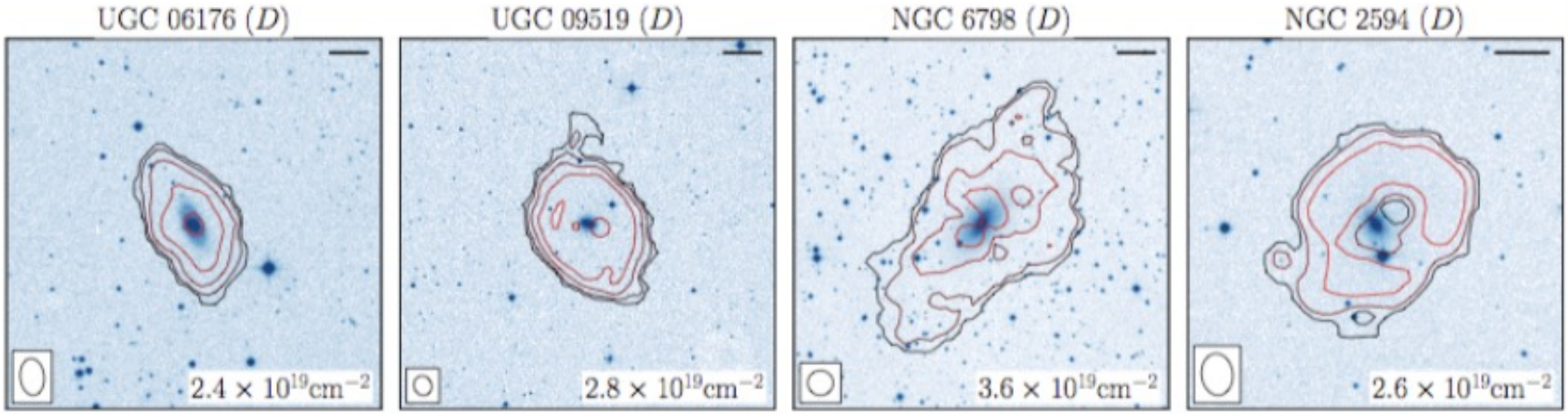
The large scale underdensities do appear to affect the growth of galaxies, as only low mass systems are found in voids, but…

The properties of these small galaxies are not different from small galaxies in higher density environments contrary to the predictions

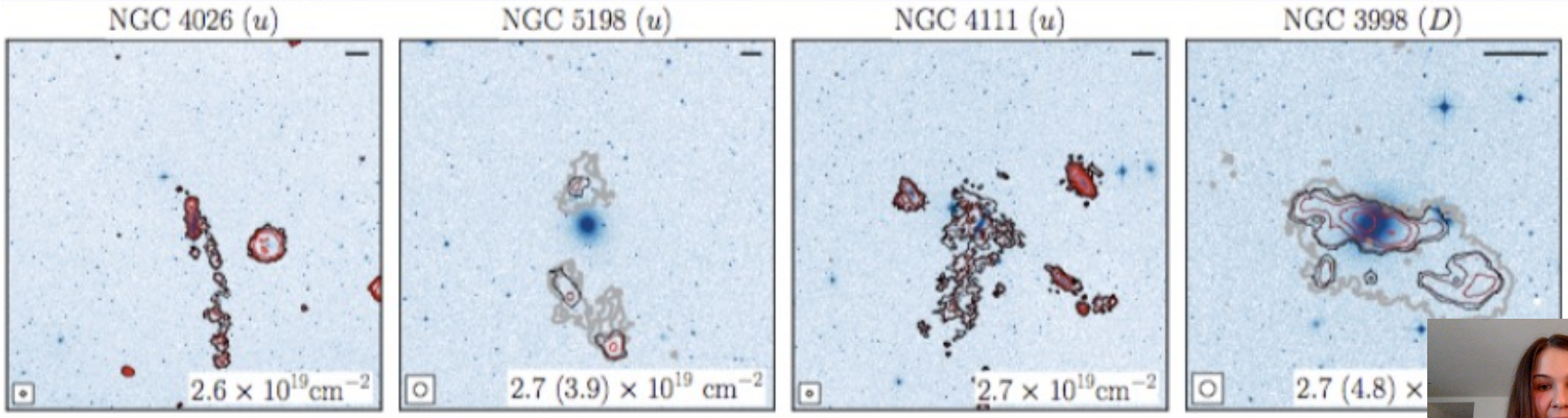


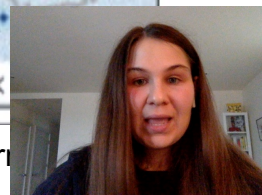
HI in Early type galaxies

Low density regions



High density regions



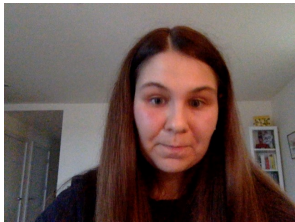


Ser

Take Home Messages II

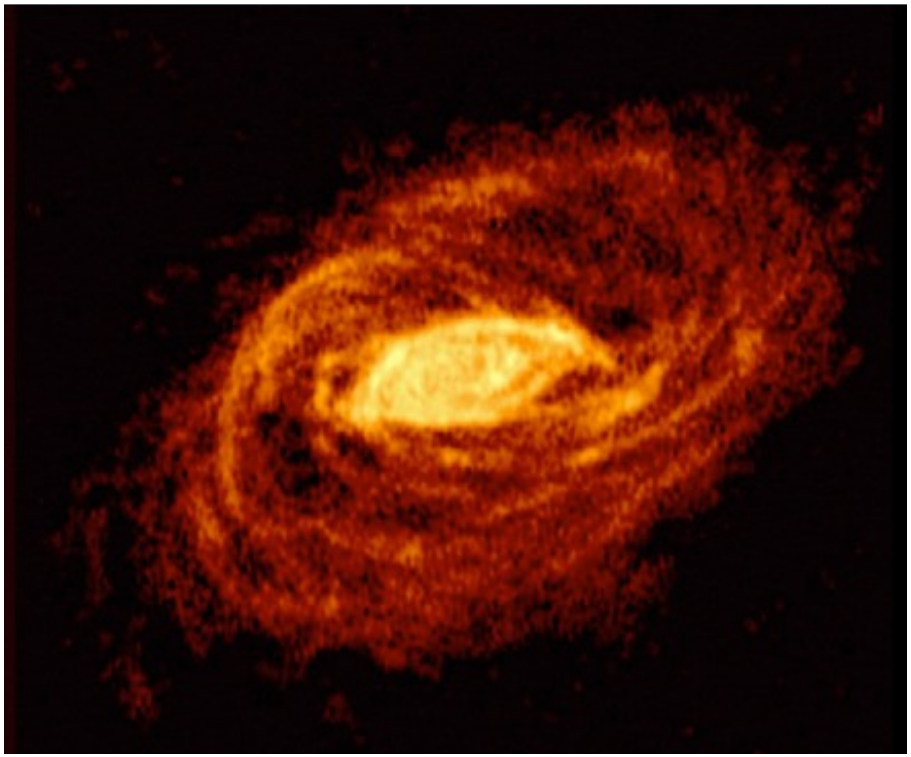
Imaging of HI morphologies reveals a wealth of information on physical processes relevant for galaxy formation and transformation mechanisms not detectable otherwise:

- HI disks extend far beyond optical radius deep into the Dark Matter halo
- Galaxies have constant average HI surface mass density
- HI is an excellent tracer of the environment

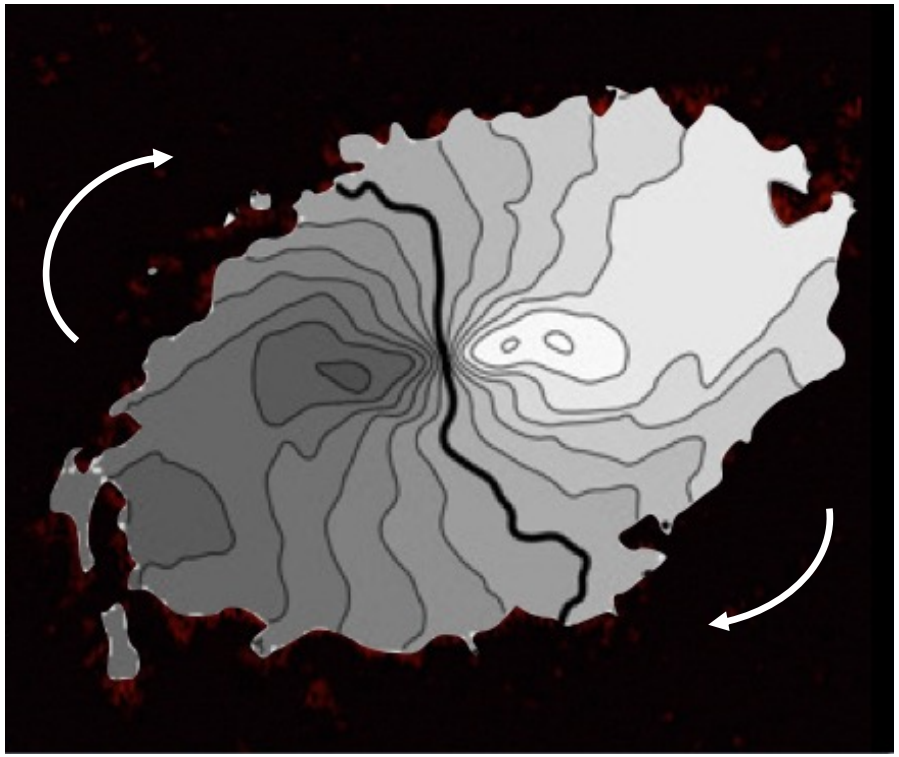


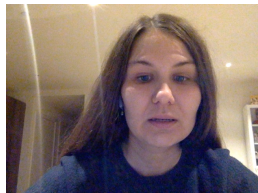
HI Kinematics

HI intensity

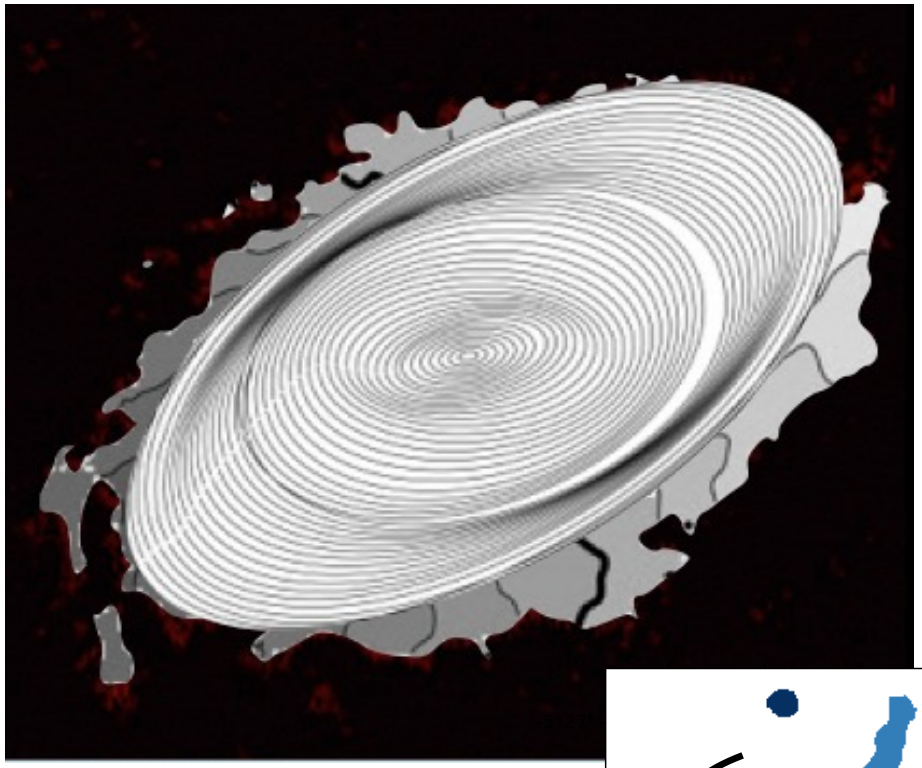


HI Line-of-Sight Velocity





HI Kinematics



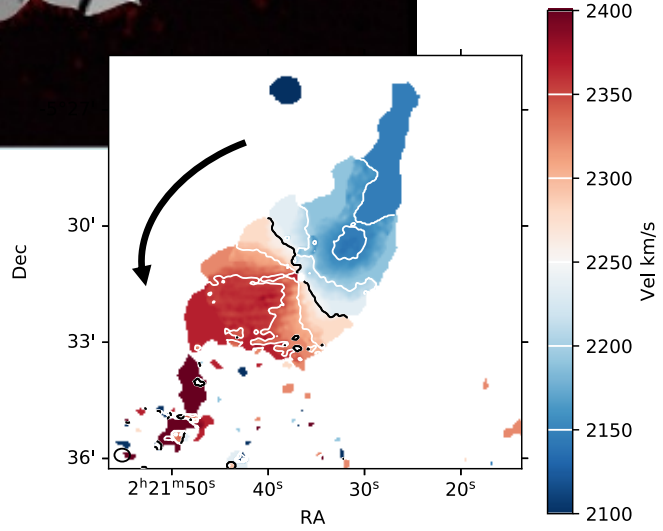
Tilted ring model

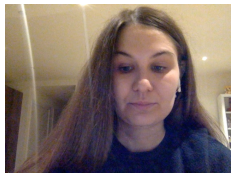
$$V_{rot} = \frac{V_{los} - V_{sys}}{\sin(i)\cos(\theta)}$$

(i) - inclination angle of a galaxy
(θ) - position angle of a galaxy

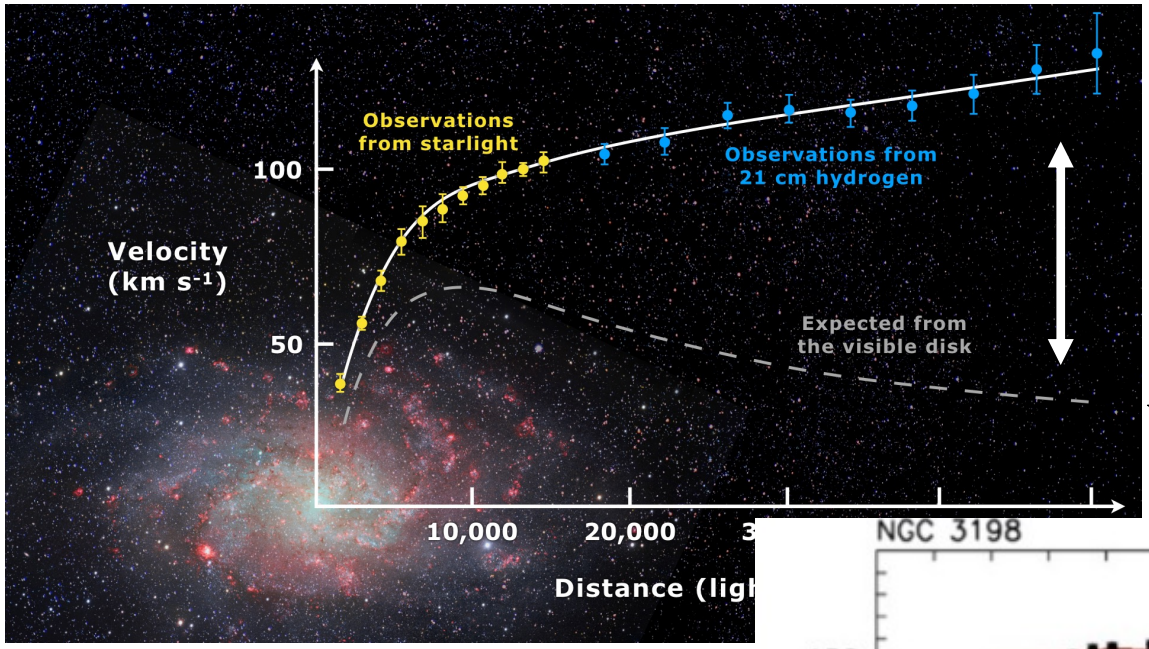
$$\cos(i) = b/a$$

Where b and a are the minor and major axis of the disk





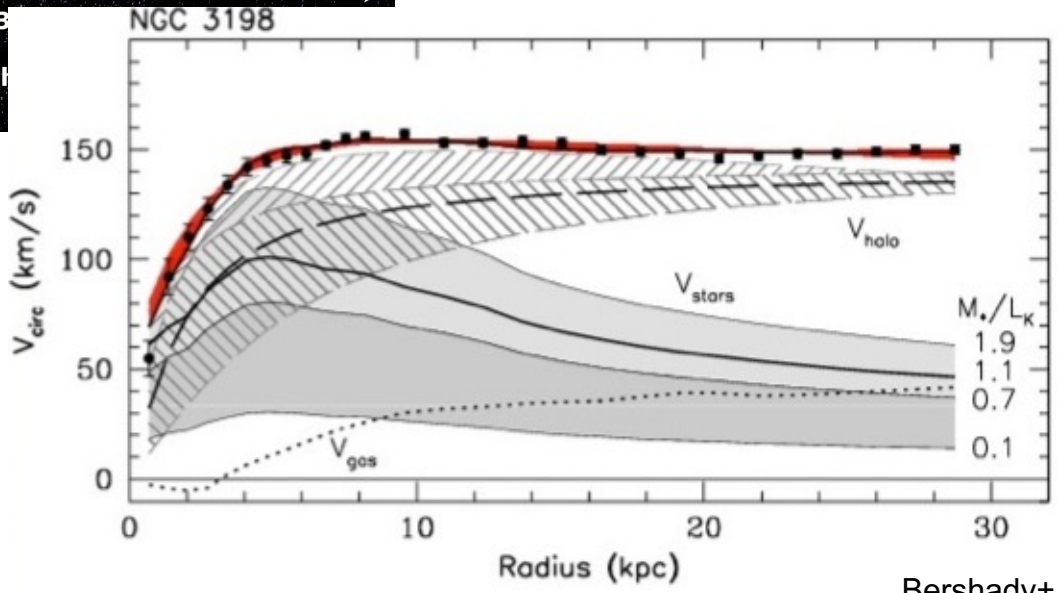
HI rotation curves and Dark Matter

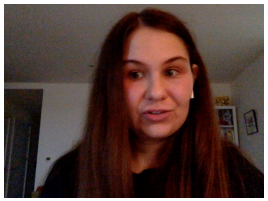


Bosma 1978
Rubin 1978, but… optical

?

$$V_{obs} = \sqrt{V_{stars}{}^2 + Vgas^2 + VDM^2}$$



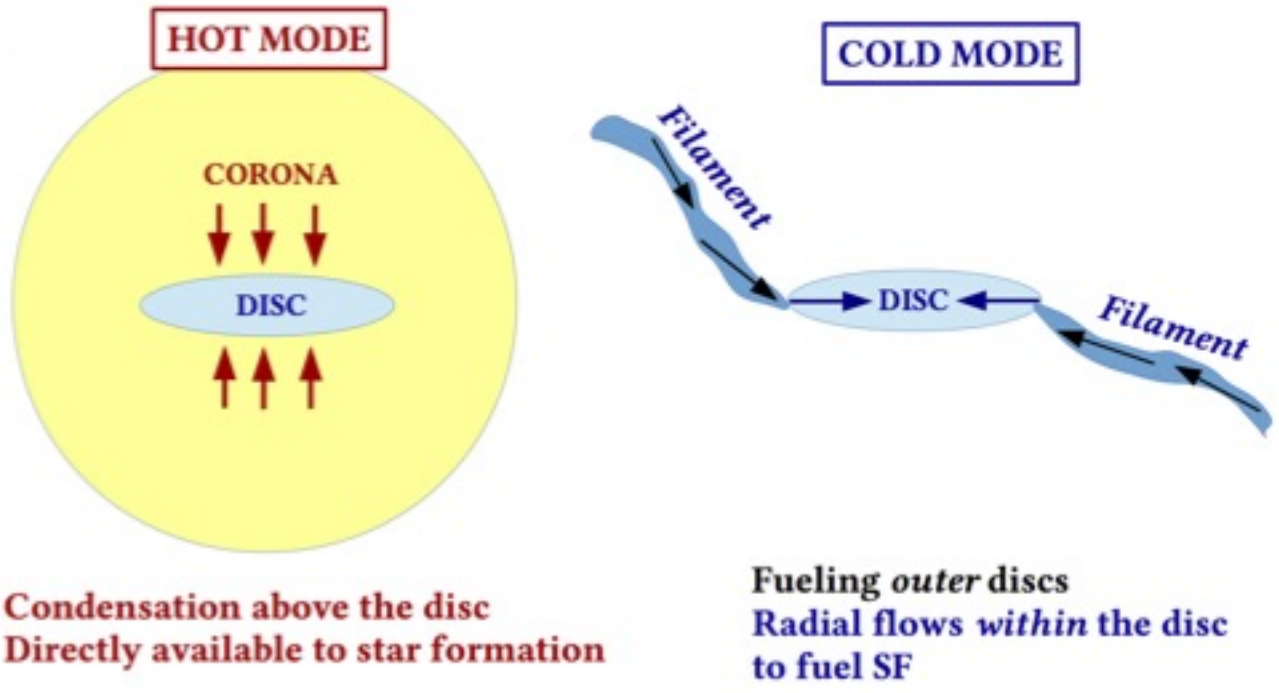


Bershady+ 10

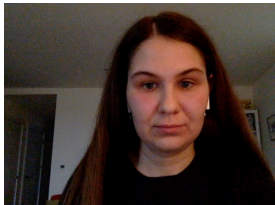
HI evidence of accretion

Star formation consumes ALL the gas in a few Gyr.
So how do galaxies keep forming stars?

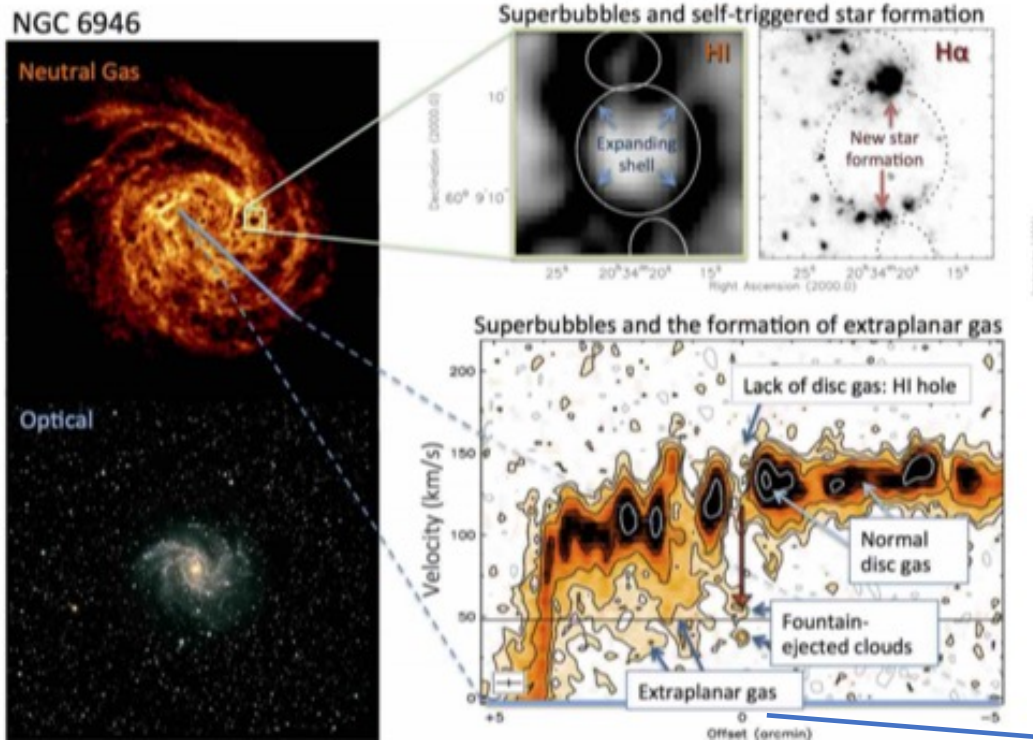
Gas Accretion



Pezzulli+16

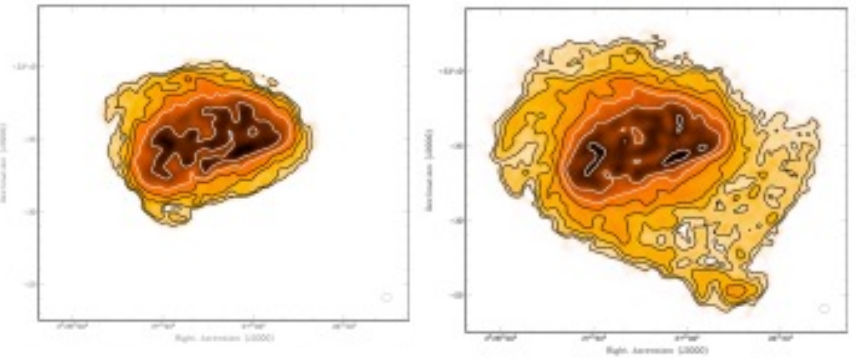


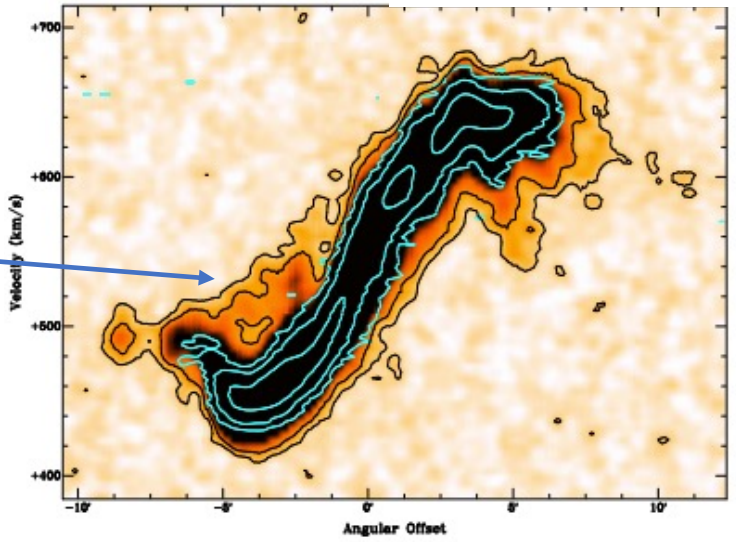
HI evidence of accretion



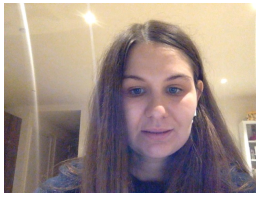
Fraternali16 (review)

NGC 925





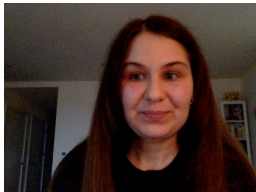
deBlok+ 15



Take Home messages III

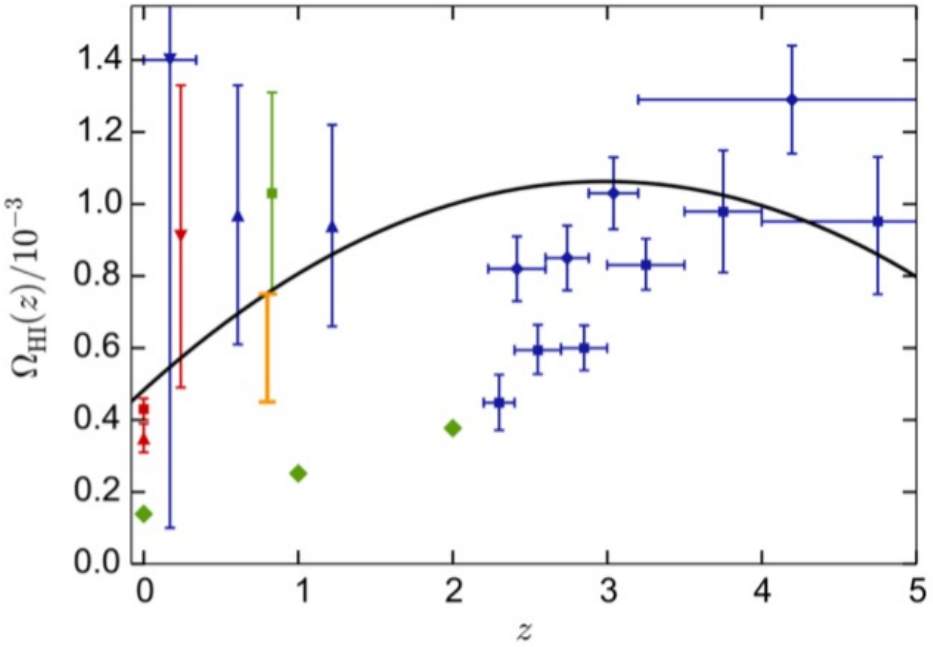
HI kinematics reveals physical processes not/hardly seen otherwise:

- Provides evidence of gas accretion, which sustains star formation
- Sheds the light on Dark Matter
- Puts constraints of cosmological models of galaxy formation and evolution, e.g. the shape of the DM halo density profile



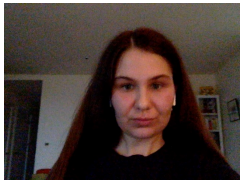
HI Limitations

The measured HI density is poorly constrained beyond $z = 0$



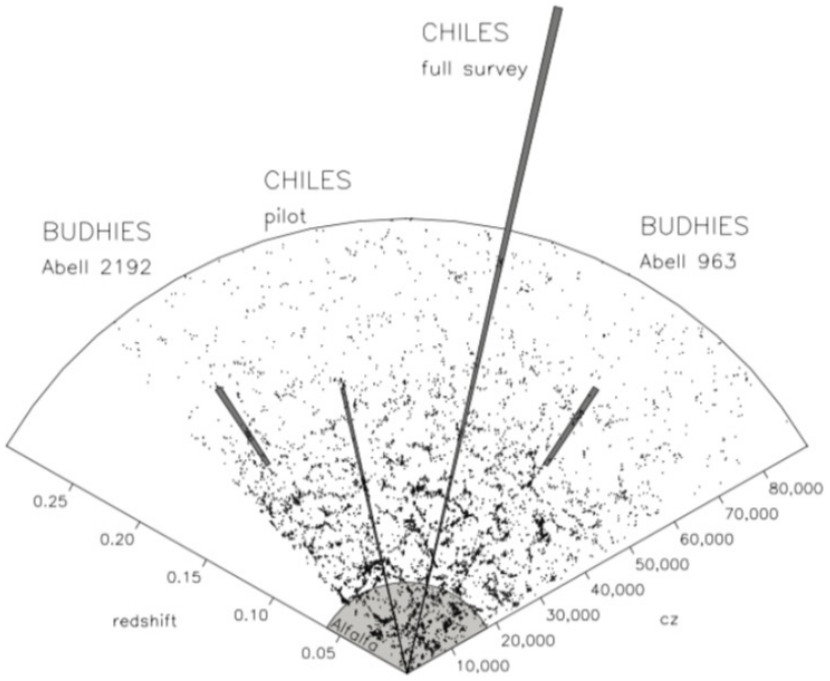
- HI observations are limited to the Local Universe z < 0.1
- HI is extremely faint: need long integration time and high sensitivity
- Technical limitations

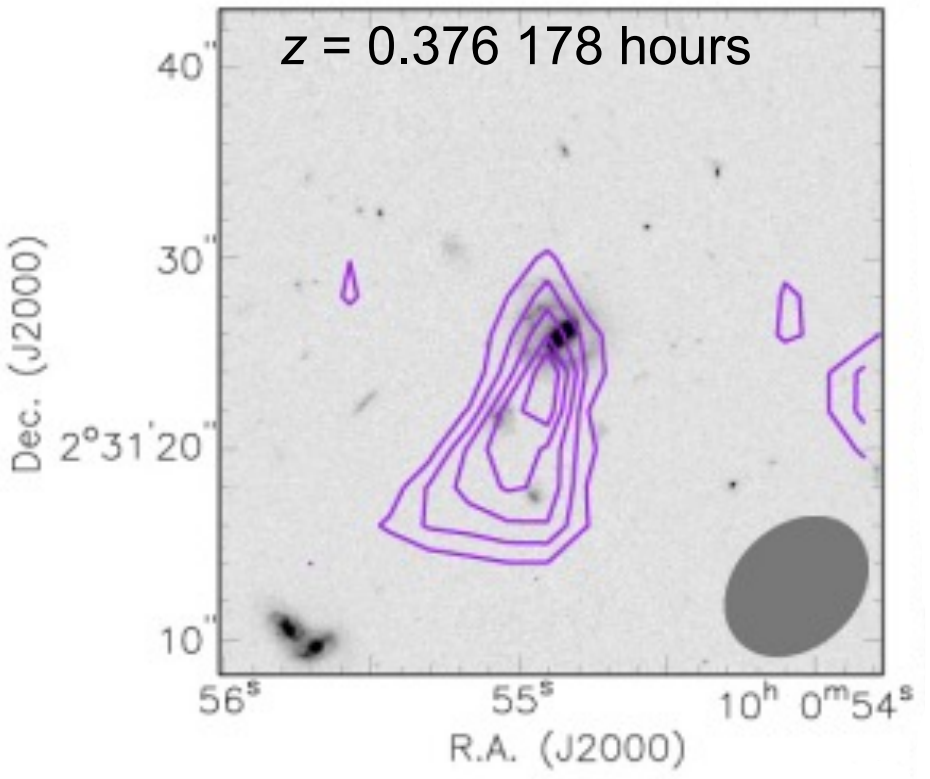
Santos+ 15

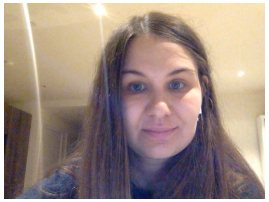


HI beyond the local Universe

CHILES
COSMOS HI LARGE EXTRAGALACTIC SURVEY







Fernandez+ 16

The Future of HI Studies

SKA pathfinders

South Africa

MeerKAT HI Surveys:

LADUMA : Looking at the Distant Universe with the MeerKAT Array
MIGHTEE-HI : The MeerKAT International GHz Tuned Extragalactic Exploration
MHONGOOSE : MeerKAT HI Observations of Nearby Galactic Objects - Observing Southern Emitters
Fornax cluster : A study of the nearby Fornax Galaxy Cluster - Galaxy formation and evolution in the cluster environment.

Australia

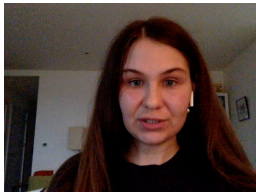
ASKAP HI Surveys:

WALLABY : The Widefield ASKAP L-band Legacy All-sky Blind surveY
DINGO : Deep Investigation of Neutral Gas Origins
FLASH : The First Large Absorption Survey in HI

The Netherlands

Apertif HI Surveys:

Shallow- Wide: a large-area, shallow imaging survey of HI
Medium Deep : imaging survey
of HI

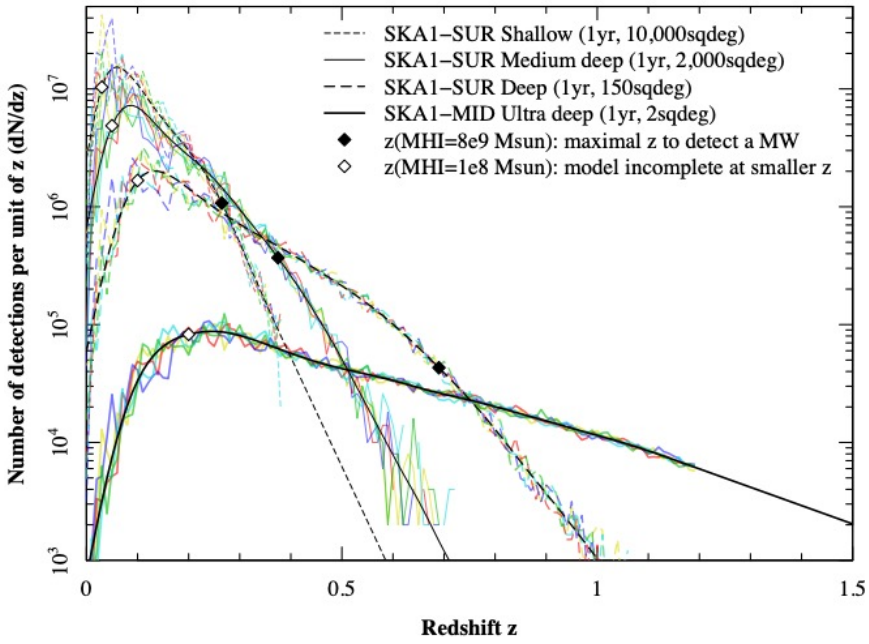


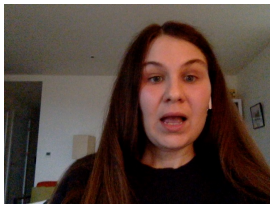
The Future of HI Studies

The Square Kilometre Array

	Shallow survey	Medium deep survey
Area	10000 deg^2	2000 deg^2
Integration time	1 yr (Sur)	1 yr (Sur)
Resolution	10"	5"
z (M_{HI}*)	0.27	0.37
mean z	0.08	0.11
nr. of detections	2.02E+06	1.20E+06

	Deep survey	Ultra Deep Survey
Area	150 deg^2	2 deg^2
Integration time	1 yr (Sur)	1 yr (Mid)
Resolution	3"	2"
z (M_{HI}*)	0.69	1.7
mean z	0.19	0.37
nr. of detections	4.60E+05	4.20E+04



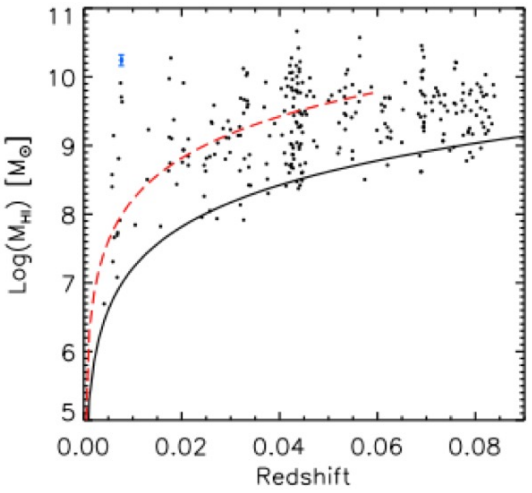


Conclusions

- Imaging of HI morphologies and kinematics reveals a wealth of information on physical processes relevant for galaxy (trans)formation mechanisms not detectable otherwise

- Future blind surveys with SKA pathfinders (like MeerKAT) will yield ~10^5 HI images/cubes across all environments with sufficient resolution and sensitivity

MIGHTEE-HI Survey



- Pathfinders are pushing HI detections & resolved HI distribution and kinematics beyond z = 0

- SKA will change everything we know!